

1 Benfotiamine in Alzheimer's Disease: A Pilot Study

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3 NCT02292238

4 **September 2, 2020**

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**Background.** In preclinical models, benfotiamine efficiently ameliorates the clinical and biological pathologies that define Alzheimer's disease (AD) including impaired cognition, beta amyloid plaques, neurofibrillary tangles, diminished glucose metabolism, oxidative stress, increased advanced glycation end products (AGE) and inflammation.

**Objective.** To collect preliminary data on feasibility, safety and efficacy in individuals with amnesic mild cognitive impairment (aMCI) or mild dementia due to AD in a placebo-controlled trial of benfotiamine.

**Methods.** A twelve-month treatment with benfotiamine tested whether clinical decline would be delayed in the benfotiamine group compared to the placebo group. The primary clinical outcome was the AD-Assessment-Scale-Cognitive Subscale (ADAS-Cog). Secondary outcomes were the clinical dementia rating (CDR) score and fluorodeoxyglucose (FDG) uptake, measured with brain positron emission tomography (PET). Blood AGE were examined as an exploratory outcome.

**Results.** Participants were treated with benfotiamine (34) or placebo (36). Benfotiamine treatment was safe. The increase in ADAS-cog was 43% lower in the benfotiamine group than in the placebo group, indicating less cognitive decline, and this effect was nearly statistically significant ( $p=0.125$ ). Worsening in CDR was 77% lower ( $p=0.034$ ) in the benfotiamine group compared to the placebo group, and this effect was stronger in the APOE  $\epsilon 4$  non-carriers. Benfotiamine significantly reduced increases in AGE ( $p=0.044$ ), and this effect was stronger in the APOE  $\epsilon 4$  non-carriers. Exploratory analysis derivation of an FDGPET pattern score showed a treatment effect at one year ( $p=0.002$ ).

**Conclusions** Oral benfotiamine is safe and potentially efficacious in improving cognitive

outcomes among persons with MCI and mild AD.

## INTRODUCTION

Alzheimer's disease (AD) therapies targeting brain amyloid- $\beta$  ( $A\beta$ ) have in most cases shown a lack of efficacy, suggesting that AD treatment development should consider alternative targets. In addition to plaques, tangles and cognitive decline, multiple changes accompany AD including inflammation, oxidative stress and metabolic dysregulation. Cerebral glucose metabolism as measured by fluorine-18 ( $^{18}\text{F}$ ) fluorodeoxyglucose positron-emission tomography (FDGPET) changes decades before AD is typically diagnosed [1], and in AD patients reductions in glucose utilization correlate highly with cognitive decline [2].

Abnormalities in glucose metabolism, vascular changes and inflammation are closely linked and common features of AD [3, 4]. Thiamine diphosphate (ThDP)- dependent enzymes regulate key steps in brain glucose metabolism, and the activities of ThDP-dependent enzymes decline in blood and brain of AD patients. The reduction in the activity of these enzymes provide a plausible underlying mechanism for the metabolic abnormalities [5-7]. In pre-clinical models, thiamine deficiency induces inflammation and change in vasculature [8]. Abnormal metabolism often leads to over production of free radicals that damage other molecules. At autopsy, oxidative stress in the brain is as widespread as plaques and tangles [9]. Increases in Advanced Glycation End products (AGE), toxic protein modifications that are indicative of altered glucose metabolism, and their receptor, RAGE, occur in the brain [10] and periphery [11] of AD patients, in both plaques and tangles [12].

Benfotiamine, a synthetic thiamine precursor, has direct actions on multiple metabolic enzymes and pathways, inflammation and oxidative stress [13, 14]. Benfotiamine's activation of the enzyme transketolase [15] accelerates the shunting of the precursors of AGE towards the pentose phosphate pathway thereby reducing the production of AGE [16, 17]. The reduction in AGE decreases metabolic stress, which reduces vascular complications [18-21]. By being more effective in raising blood thiamine concentrations than direct thiamine administration, benfotiamine may overcome the reduction in activity of ThDP dependent enzymes in AD [18, 19]. For example, mice [22] and humans [23] that have genetic defects in the thiamine transporter can be treated with high dose benfotiamine. Benfotiamine is an antioxidant [24-26], modulates arachidonic acid inflammation pathways, nuclear transcription Factor  $\kappa$ B (NF- $\kappa$ B), protein kinase B, mitogen-activated protein kinases (MAPK) and vascular endothelial growth factor receptor 2 (VEGFR2) signaling pathways [14]. Recent studies suggest that restoring cerebral perfusion by preventing neutrophil adhesion may provide another strategy for improving cognition in AD participants [27]. Benfotiamine prevents lipopolysaccharide (LPS)-induced macrophage death and monocyte adhesion to endothelial cells [28]. Multiple approaches suggest that benfotiamine inhibits inflammatory mediators and enhances anti-inflammatory factor production in activated microglia [28, 29].

Benfotiamine diminishes pathology in multiple pre-clinical models of disease including animal models of AD, which have human gene mutations that cause AD [25]. In a transgenic mouse model of tauopathy, benfotiamine treatment diminishes tangles, activates the Nrf2/ARE pathway, neuroprotective and improves behavioral deficits [30]. In animal models of amyloid plaque formation, benfotiamine reduces amyloid plaque numbers and phosphorylated tau levels, elevates the phosphorylation of glycogen synthase kinase-3 $\alpha$  and -3 $\beta$ , and improves memory

[31]. In other animal models, benfotiamine modulates activation of GSK3- $\beta$  [32], restores neurogenesis [26, 33], modulates AMPA receptor expression [25] and decreases oxidative stress [26]. Together, these results suggest that benfotiamine may be therapeutically beneficial for AD.

Benfotiamine also diminishes AGE. Measures of AGE in the serum assess peripheral abnormalities and may mirror CNS abnormalities in glucose homeostasis. AGE are a biomarker implicated in aging and the development, or worsening of many degenerative diseases, such as diabetes, atherosclerosis, chronic renal disease, and AD. High concentrations of AGE appear predictive of long-term decline in cognition-related daily living performance in patients with AD as measured by Clinical Dementia Rating (CDR) [11] or Mini Mental Status Exam (MMSE)[34]. Thus, AGE may be a promising therapeutic target to prevent or delay the progression of AD [35]. Numerous studies in patients with diabetes show that benfotiamine diminishes AGE [21]. A preliminary study of five patients without placebo control that was published after our trial was initiated showed promise [36].

Benfotiamine is safe compound in AD patients as demonstrated in trials conducted for the treatment of peripheral neuropathy in diabetes [13, 20, 37]. The dosage studied most extensively in diabetics is 300 mg in the morning and night, but dosages as high as 900 mg per day show no significant toxicity [20].

The aim of this study was to conduct a double-blind early phase II randomized placebo-controlled trial of benfotiamine with the objective of collecting preliminary data on feasibility, safety, and efficacy. The goal was to test whether benfotiamine treatment could delay clinical decline in amyloid positive patients with amnesic mild cognitive impairment (aMCI) or mild dementia due to AD with MMSE scores of >21. ADAS-cog served as the primary endpoint.

Brain glucose utilization, measured using FDG PET imaging, was assessed as a secondary endpoint. Cerebral glucose metabolism declines in temporoparietal regions with the progression of AD, correlates with clinical decline, and is also a sensitive measure of changes in regional neuronal function associated with disease or treatment effect [1, 2]. AGE levels were used as a peripheral marker of efficacy. Measures of thiamine and its esters thiamine diphosphate (ThDP) and thiamine monophosphate (ThMP) provided blood markers of efficacy of drug delivery.

## MATERIALS AND METHODS

This clinical trial was a collaborative study between investigators at the Burke Rehabilitation Center including the Burke Rehabilitation Hospital and the Burke Neurological Institute [an affiliate of Weill Cornell Medicine (WCM)], WCM, and investigators at Columbia University Irving Medical Center (CUMC). The trial was approved by the Institutional Review Boards of the Burke Rehabilitation Hospital, WCM and CUMC.

### **Patient population.**

Seventy amyloid positive patients 60 years and older with aMCI ( $21 < \text{MMSE} < 26$ ) or mild AD dementia ( $\text{MMSE} \geq 26$ ) were included. Table 1 shows the inclusion and exclusion criteria for what we define as AD in this trial. These criteria are especially important because new imaging capabilities will likely redefine AD [38].

### **Study design.**

**Sample size justification.** In addition to literature that states a four-point change on the

ADAS-Cog is considered clinically significant, several randomized clinical trials have found ADAS-Cog change scores differed by 3-4 points between placebo and treatment groups over a 6-month time period. Moreover, other studies report annual changes in the ADAS-Cog among those who are untreated to average 9.6 points (SD=8.2) [39, 40]. Power was calculated based on expected difference in change on the ADAS-COG of 3 points between the treatment and control groups. Estimates based on using a two-sided alpha of 0.05 and a standard deviation of 4, enrolling 29 patients per group, (N=58) suggest 80% power to detect a mean change of 3 between treatment and placebo.

**Assignment of patients.** A randomized, placebo-controlled, double-blinded trial of benfotiamine in persons with aMCI or AD dementia with a duration of 12 months was conducted. Using blocked, stratified randomization design, patients were assigned to the treatment or control group. By the inclusion criteria all subjects had MMSE of >21. Within this group, a separate randomization schedule was generated using the proc plan function in SAS statistics program for those with an MMSE greater than or less than or equal to 26 to balance their allocation patients to placebo or treatment groups. Using a block size of four for a total of seventy-six patients, 19 blocks were created to help ensure balanced recruitment into treatment and control groups within strata. The schedule was generated in advance by the statistician and provided to the blinded pharmacist in charge of executing the randomization. Two randomization worksheets stratified by MMSE were provided to the pharmacist, who randomized the patients. One sheet had MMSE Scores  $\geq 26$  (randomized to Active or Placebo). The other sheet had MMSE scores  $< 26$ . The patients were enrolled by the clinical study team and randomized by the pharmacist. The assignment to the treatment or placebo group was known only to the pharmacist and kept behind a triple lock. The patients received numbered bottles.

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139           **Study procedures.**

140           The trial was registered in ClinicalTrials.gov (NCT02292238 (Figure 1). Participants  
141 were pre-screened from the database of the Memory Evaluation Treatment Service (METS) at  
142 Burke Rehabilitation Center or referrals from the Center for the Aging Brain (CAB) at  
143 Montefiore/Einstein Medical College, Alzheimer’s Association, primary care physicians, and  
144 private neurologists from the lower Hudson Valley region. aMCI or mild AD dementia were  
145 diagnosed according to NIA-AA workgroups criteria [41, 42]. Patients who met the inclusion  
146 criteria for aMCI or mild dementia due to AD were invited for a screening initial visit at the  
147 Memory Evaluation and Therapeutic Service (METS) outpatient department at the Burke  
148 Rehabilitation Hospital. After informed consent was obtained from patients and their health care  
149 proxies, a physical examination including EKG, laboratory tests (Complete Blood Count,  
150 Complete Metabolic Panel, Vitamin B12, folate, Thyroid function tests), a neurological exam  
151 and the MMSE were administered. If eligible (Table 1), participants were referred to  
152 Westchester Imaging Center for an Amyloid PET/CT scan of the brain. Only participants with a  
153 positive amyloid scan were sent to CUIMC for a baseline F-18-FDG PET/CT scan of the brain.  
154 At the baseline visit, the cognitive tests were performed and blood drawn for measurement of  
155 thiamine, ThDP and ThMP by HPLC [43] and APOE genotyping. Enrolled patients returned to  
156 the Burke outpatient clinic at month 3, 6, 9 and 12 for subsequent visits. At month 12 the final  
157 FDG/PET scan was performed at CUIMC.

158           The trial duration per participant was twelve months. Participants in the treatment group  
159 took one 300 mg capsule of benfotiamine in the morning and one in the evening. The



participants in the placebo group took one 300 mg capsule in the morning and evening with microcrystalline cellulose without benfotiamine. At each visit, the patients returned the pill bottles for that period. The number of pills returned was used to assess compliance (the percent of pills consumed).

#### **Characterization procedures.**

**Amyloid scans.** Amyloid- $\beta$  was assessed using PET imaging with  $^{18}\text{F}$ -Betapir F18 PET [44] to help confirm the presence of AD pathology in study participants. Positivity was determined by a visual read.

**APOE Genotyping Method.** Total nucleic acid was isolated from whole blood samples for *APOE* genotyping using the MasterPure™ Complete DNA and RNA purification kit (Lucigen) with a starting volume of 150  $\mu\text{l}$  of blood, according to the manufacturer's instructions. Genotyping of the two human *APOE* polymorphisms was carried out using the TaqMan® SNP genotyping assays (ThermoFisher Scientific): C\_3084793\_20 for SNP rs429358 and C\_904973\_10 for SNP rs7412. An initial 5 min step at 95°C was followed by 40 cycles of 15 s at 95°C and 30 s at 60°C. Genotyping was performed in duplicate with controls for all six possible *APOE* genotypes and no DNA controls using a QuantStudio™ 12K Flex real-time PCR system (ThermoFisher Scientific).

#### **Treatment.**

The trial duration per participant was twelve months. Participants in the treatment group took one 300 mg capsule of benfotiamine in the morning and one in the evening. The participants in the placebo group took one 300 mg capsule in the morning and evening with

microcrystalline cellulose without benfotiamine. At each visit, the patients returned the pill bottles for that period. The number of pills returned was used to assess compliance (the percent of pills consumed). The benfotiamine and placebo were manufactured and provided by the Advanced Orthomolecular Research, Canada. They prepared the benfotiamine according to an FDA-approved IND, which was prepared by the Cornell Translational Science Center, and issued to the Burke Neurological Institute.

### **Cognitive measures.**

The following cognitive tests were conducted at the intervals indicated in Figure 1:

- **AD Assessment Scale-Cognitive Subscale (ADAS-Cog)** was the primary outcome measure. It indicates the severity of the most important symptoms of Alzheimer's disease. It consists of 11 tasks measuring the disturbances of memory, language, praxis, attention and other cognitive abilities [45] [46].
- **Clinical dementia rating (CDR) score.** CDR is a 5-point scale used to characterize six domains of cognitive and functional performance applicable to Alzheimer disease and related dementias: Memory, Orientation, Judgment & Problem Solving, Community Affairs, Home & Hobbies, and Personal Care. A higher score indicates greater dementia [47].
- **The Buschke Selective Reminding Test (SRT)** [48] is a standard diagnostic tool in the assessment of verbal memory. Several studies attest to its predictive value for dementia [49, 50].
- **Neuropsychiatric Inventory (NPI).** The NPI assesses a wide range of behaviors encountered in dementia patients to provide a means of distinguishing frequency and

severity of behavioral changes. Ten behavioral and two neuro-vegetative domains are evaluated through an interview with the caregiver [51-53].

- **Alzheimer's Disease Cooperative Study- Activities of Daily Living (ADCS-ADL).**

The ADCS-ADLSIV is a caregiver-based ADL scale composed of 19 items developed for use in dementia clinical studies [54]. It assesses the patient's performance of both basic and instrumental activities of daily living such as those necessary for personal care, communicating and interacting with other people, maintaining a household, conducting hobbies and interests, as well as making judgments and decisions. Higher numbered scores and answers of "yes" reflect a more self-sufficient individual. Therefore, the higher total score correlates with higher cognitive function. The total score is the sum of all items and sub-questions [55].

#### **Biomarker outcomes.**

AGE are formed during the Maillard reaction where reducing carbohydrates react with lysine side chains and N-terminal amino groups of various macromolecules, particularly proteins. AGE can adversely affect the function of these macromolecules. One of the most prevalent advanced glycation end products, N-epsilon-(Carboxymethyl) Lysine, has been implicated in oxidative stress and vascular damage. The quantity of AGE adduct in protein samples is determined by comparison with that of a known AGE-BSA standard curve.

AGE levels were measured on plasma sample with a kit from ABCAM (AB238539), Cambridge, MA., USA

## **Fluorodeoxyglucose (FDG) Positron Emission Tomography (PET).**

### **Image acquisition, processing, and measurement**

FDG PET imaging of glucose metabolism was acquired at baseline and after 12 months of treatment. All scans were acquired on a Siemens MCT 64 PET/CT PET-CT scanner at CUIMC. Study participants were maintained in an awake, at rest state with eyes and ears open in dim lighting during tracer uptake. Forty minutes after injection of the tracer, the emission image was acquired in four contiguous 5-minute frames. Frames were aligned with SPM 12, averaged, and then spatially normalized to the MNI template using SPM12 <https://www.fil.ion.ucl.ac.uk/spm/software/spm12/>, resulting in one image per participant for each time point. Average voxel values within 90 regions of interest (ROIs) in the Automated Anatomic Labeling (AAL) Atlas [56] were computed. A subset of 16 pre-specified bilateral regions of interest (ROIs) were chosen for the group analysis due to their relevance to AD including: posterior cingulate, precuneus, frontal, inferior parietal, mid temporal, hippocampus, paracentral lobule, and cerebellum. The paracentral lobule and cerebellum were included as reference regions given their relative preservation during AD progression.

### **Derivation of spatial covariance patterns for Glucose FDGPET.**

A multivariate machine learning approach was also applied to evaluate the FDG PET data (Figure 10). Pattern-based methods have been increasingly applied to the evaluation of neurodegeneration and therapeutic response as they address the issue of complexity in comparing multiple regions and can increase signal to noise for analysis. Feature reduction was performed through use of the Scaled Subprofile Model (SSM) [57-61], a form of Principal Components

Analysis (PCA). The resulting components were used in regression modeling that determined spatial patterns of hypometabolism and hypermetabolism (or preservation relative to other regions) associated with the Clinical Dementia Rating (CDR) score.

Specifically, SSM by performing PCA on the PET-data array was run, with a subsequent brain-behavioral regression to derive a best-fitting pattern whose pattern scores correlates with the CDR score in a negative direction (i.e. the higher the pattern score, the lower the CDR). The best-fitting set of Principal Components was obtained via the Akaike criterion [62], and came out as PC1-2.

To help with the imputation of the multivariate analysis, a generic multivariate decomposition was written as:  $Y(s, \mathbf{x}) = w(s) v(\mathbf{x}) + \varepsilon(s, \mathbf{x})$ , where  $Y$  denotes the (log-transformed) data which depends on a participant and time index  $s$  and the voxel location  $\mathbf{x}$ . The pattern score  $w(s)$  is a scalar that solely depends on subject and time, but not voxel location, whereas the derived pattern  $v(\mathbf{x})$  depends on voxel location, but shows invariance across participants and time, i.e. does not depend on index  $s$ ;  $\varepsilon(s, \mathbf{x})$  denotes residual signal that is dependent on participant, time and voxel location, but which was discarded for our purposes. The pattern score  $w(s)$  was chosen to correlate negatively with CDR across the data. The pattern  $v(\mathbf{x})$  is normalized to have unity Euclidean norm, i.e.  $\|v\|=1$ . This means that the pattern score carries all information about the strength of the signal associated with the spatial pattern. Higher values of  $w(s)$  imply higher values of pattern-associated FDGPET signal in direct proportion in all regions.

To estimate the topographic robustness of any patterns of interest, a bootstrap resampling procedure [63, 64] was performed 10,000 times, for which data were resampled with

replacement and the complete analytic recipe was executed on the resampled data, generating distribution for pattern loadings. Regional loadings were considered robust if the 95% coverage interval ( $= [2.5\%, 97.5\%]$ ) did not overlap with, and lay to one side of, zero. For the correct interpretation, it is important to keep in mind that positive and negative loadings describe only *relative*, and not *absolute* differences, in the signal associated with any covariance pattern. Since the residual signal in  $\epsilon(s, \mathbf{x})$  was stripped off, there cannot be assurance that there are absolute differences in the total data for the regions with robust loadings.

After deriving and estimating the topographic robustness of the pattern, the pattern score was inspected for an effect of treatment at baseline and follow-up, also broken down by APOE  $\epsilon 4$  status.

## **Statistical methods [65, 66]**

Our primary clinical outcome was ADAS-Cog and secondary outcomes were the CDR score and fluorodeoxyglucose (FDGPET) imaging of the brain. AGE levels were an exploratory outcome.

Our primary analysis followed Intention-to-Treat (ITT) and the secondary analysis was per-protocol. The per-protocol analysis omitted one placebo participant who took benfotiamine from a commercial vendor. The ITT and per-protocol analysis are presented for the primary outcome ADAS-cog and the secondary measure CDR. For the other measures only per-protocol analysis are presented.

Spearman correlation coefficient was used to assess the correlation between continuous variables. *Student's t*-test was used to compare the continuous variables between placebo and treatment groups; Fisher's exact test was used to compare categorical variables between placebo and treatment groups. Specifically, two-sample *Student's t*-test was used to compare the score changes (ADAS score, normalized PET-related scores, etc.) from baseline between Placebo and Treatment groups when normality was satisfied, otherwise Wilcoxon Rank-sum test was used. ANCOVA was used to test the group difference while adjusting for covariates.

The primary analysis was done on the ITT data. The Last-Observation-Carry-Forward (LOCF) method was used to impute the missing values of ADAS total score and the secondary endpoints such as CDR as well for each time point. The primary analysis was done on ITT data which were imputed with LOCF method. Per-protocol analysis was done as a sensitivity analysis and as observational comparisons [66].

In the time to event analysis, time to  $\geq 3$  points of ADAS change was calculated based on whether the ADAS score changed from baseline  $\geq 3$  (event) at each time point. When no change  $\geq 3$  points was observed at any time point, the observation is censored and the last follow-up time (12 month) was used to calculate the duration. Kaplan-Meier estimator was then used to estimate probability of time-to-event. The difference between groups was tested by log-rank test for statistical significance.

As sensitivity analyses, repeated-measure ANOVA, generalized estimating equation (GEE) and Mixed effect model and Wilcoxon Rank-sum test were also performed on primary endpoints with and without imputation to compare differences between placebo and treatment groups.

Subgroup analyses in MMSE, APOE and sex were either in the per-protocol analysis or exploratory. A *Student's t*-test was used in each of the subgroup comparisons. An ANCOVA was also used to analyze the treatment difference while adjusting for each of these covariates. Interaction between MMSE and ADAS-cog responses was assessed by ANCOVA with interaction term. Multiple comparisons were present in our analyses with secondary endpoints, subgroup analyses, or analyses with multiple PET-related scores. Due to exploratory nature of those analyses and early trial of this study, we did not apply correction of p-values for multiple comparisons. All statistical tests were two-sided with an alpha level of 0.05 as the significance cutoff. All analyses were performed in statistical software SAS Version 9.4 (SAS Institute, Cary, NC).

## Results

### Characteristics of the populations at baseline.

The first participant entered the trial on February 12, 2015 and the final participant finished July 9, 2019. This allowed us to exceed our enrollment goal of 58. Pre-screening of 634 patients at the METS at the Burke Rehabilitation Hospital excluded all but 120 participants (Figure 1). Only eighty-three of these patients were amyloid positive. Twelve declined to participate. Seventy-one of these participants agreed to be part of the trial, and were randomized to receive either placebo or benfotiamine. Eight subjects were prematurely discontinued from the trial prior to Month 12. Three participants were withdrawn due to non-compliance <80%; three withdrew consent due to unwillingness to complete study procedures; one participant was lost to



follow-up and one was withdrawn by PI due to physical limitations. Patients with uncontrolled diabetes were excluded. Eight patients were being successfully managed for diabetes. Patients had to have an HbA1c < 8% and/or a fasting glucose < 200 mg/dl to be enrolled in the trial. None of the participants randomized to the treatment group withdrew due to adverse reactions or adverse effects. Since the ones who withdrew did not have final scores, their dropout did not affect 12 month scores. After the trial completion and after the data were locked, one patient in the placebo group was determined to be on benfotiamine from another source and was excluded from the per-protocol analysis. Thus, 37 (placebo) and 34 (benfotiamine) were included in the ITT analysis, and 36 (placebo) and 34 (benfotiamine) were included in the per-protocol analysis.

Whether the patient took the required medication was referred to as compliance. If the patients who withdrew are included, the percent compliance in the placebo group was 87.7 (3.5)% and in the treatment group was 89.8 (3%). If the patients that withdrew are not included, the percent compliance in the placebo group was 94.1 (1.3)% and in the treatment groups percent compliance was 94.8 (1.4)% .

The demographic characteristics of the patients are described in Table 2. The randomization procedure was based on the order of patient entry into the study. There were no statistically significant differences in age, race, MMSE, and demographic or clinical characteristics. The goal to recruit patients with an average MMSE of 26 was met. The percentage of females in the benfotiamine group (67.6%) was higher than in the placebo group (50%). Although the distribution by race was similar, only 2.9% of the population was Non-Hispanic Black. The distribution of APOE ε4 carriers and non-carriers (60% and 40%, respectively) in the whole population was reflected in the benfotiamine (64.7 and 35.3%,

respectively) and placebo (55.6% and 44.4%, respectively) groups. Nearly identical proportions were also observed for males (58.6% and 41.4%) and females (61% and 39%). The scores on the neuropsychological tests at baseline did not differ between the two groups, with the exception of NPI, which differed between groups at baseline ( $p=0.040$ ) (Table 2B).

Baseline thiamine and ThMP, but not ThDP distributions were similar in the two groups. Blood thiamine diphosphate (ThDP) was lower ( $p=0.038$ ) in the benfotiamine group (Table 2C). In agreement with the literature [67], ThDP was lower in females than males ( $p=0.0003$ ). At baseline, ThDP did not correlate with MMSE ( $p=0.644$ ), CDR ( $p=0.618$ ), ADAS-cog ( $p=0.883$ ) or whole brain glucose utilization ( $p=0.644$ ).

Baseline FDGPET measures are presented in Table 2D. In agreement with prior findings FDG PET in whole brain at baseline correlated with the MMSE (Spearman correlation,  $r=0.288$ ,  $p=0.015$ ). Brain glucose utilization was 4.4% higher in females than males ( $p=0.003$ ). At baseline, FDG PET in the mid-temporal region was significantly higher in the benfotiamine treatment group than placebo group ( $p=0.020$ ), and the cingulate was higher in the treatment group at trend level ( $p=0.069$ ) (Table 2D).

**Safety profile.** No adverse events related to the 2 X 300 mg benfotiamine per day were observed and patients did not complain about the medication (Table 3A).

**Benfotiamine and ADAS-Cog changes (Figure 2, Table 3B).** A comparison of unadjusted changes from baseline to 12 months with ITT analysis revealed a difference between the benfotiamine and placebo groups favoring benfotiamine using a mixed effect model ( $p=0.071$ ), GEE ( $p=0.137$ ), and a non-parametric Wilcoxon rank sum test ( $p=0.098$ ) (Figure 2,

Table 3B). At 12 months, the change in the placebo group was 3.26 whereas in the benfotiamine group the change was 1.39. This difference was not apparent at 3, 6 or 9 months. The per-protocol analysis (Table 3B) suggested that the differences were significant when analyzed by a mixed effect model ( $p=0.035$ ), GEE ( $p=0.069$ ) or Wilcoxon Rank-Sum ( $p=0.049$ ). The sub-category exploratory analysis of ADAS-cog revealed that the changes from baseline in the commands component ( $p=0.001$ ) and the word finding difficulty ( $p=0.033$ ) were significant at 12 months.

An exploratory analysis of effect modification by sex suggests that males might have been more responsive to benfotiamine, although none of the differences were statistically significant. Furthermore, there was no effect modification by APOE  $\epsilon 4$  allele carrier status. Finally, no significant correlation occurred between blood thiamine, ThDP or ThMP values and ADAS-cog. No significant interaction was found between MMSE score and ADAS-cog response ( $p=0.122$ ), but a *post-hoc* analysis suggested that benfotiamine had a stronger response among those with a higher MMSE at baseline (MMSE  $\geq 26$  difference in change ADAS-cog was significant ( $p=0.027$ ) whereas this was not the case for MMSE $<26$  ( $p=0.99$ )).

**CDR.** Mean change in global CDR from baseline to 12 months was significantly different between placebo and benfotiamine groups ( $p=0.034$ ), favoring the benfotiamine group (Figure 3). The difference in the placebo group was 0.22 whereas the change in the benfotiamine group was 0.05, corresponding to a reduction of deterioration by 77%. The mean change in CDR-SB from baseline to 12 months showed a difference at trend level between placebo and benfotiamine groups ( $p=0.078$ ). In an analysis of individual CDR subscores, the “home and hobbies score” differed between groups ( $p=0.032$ ) whereas other subscores did not differ.

APOE  $\epsilon$ 4 status (Figure 3C), but not sex (Figure 3B), was associated with a differential response to benfotiamine. The performance of males and females was not significantly different (Figure 3B). The change from baseline in females 0.219 was nearly identical to that in males. However, the non- APOE  $\epsilon$ 4 group seemed to respond much more than those with the  $\epsilon$ 4 allele (Figure 3C). Indeed, the change from baseline was significant in the non- APOE  $\epsilon$ 4 group ( $p=0.013$ ) although only eleven participants were in this category. No significant interaction was found by comparing patients that had MMSE values  $\geq 26$  vs  $< 26$  ( $p=0.878$ ).

**The Buschke SRT (Figure 4).** No significant change in the SRT ( $p=0.177$ ) nor the change in score (0.315) (Figure 4) occurred. Placebo treated participants showed a downward trend while benfotiamine treated participants had stable scores. Trend analysis shows that the non-APOE  $\epsilon$ 4 are the most responsive at 6 months (compared baseline  $p=0.028$ ) and 12 months (compared to baseline  $p=0.066$ ).

**NPI (Figure 5).** No differences in change in NPI were observed with benfotiamine treatment when the whole population was analyzed (Figure 5A). However, benfotiamine was associated with significantly reduced scores in males at month 9 (0.014) and month 12 ( $p=0.035$ ) (Figure 5B). The effects of benfotiamine were not altered by APOE4 status (Figure 5C).

**ADCS-ADL (Figure 6).** No significant differences were observed in ADCS-ADL. In the sub-analysis of sex and APOE, a trend was observed that was consistent with a beneficial effect of benfotiamine (Figure 6).

**Response of thiamine, ThDP and ThMP to benfotiamine treatment (Table 3C; Figures 7 and 8).**

The 161 fold increase in in blood thiamine indicated the administration of the drug was successful. In the placebo group, small increases for the levels of thiamine (5.5 to 13.6;  $p=0.044$ ) and ThDP (74.5 to 91.7;  $p=0.044$ ) occurred, but not ThMP (3.4 to 4.0;  $p=0.382$ ) (Table 3C). After completion of the trial, it was discovered that one patient in the placebo group took commercial benfotiamine during the trial. Consequentially, data from the patient was excluded for all per-protocol analysis. The twelve-month treatment with benfotiamine significantly elevated blood thiamine from 6.2 to 999 (161 fold) above baseline, ThDP (two fold) and ThMP (five fold) (Table 3C). Although the differences were significant, the scatter grams revealed large variations (Figure 7). These changes were apparent even though the timing between the taking the last capsule and taking blood were not standardized. The much larger changes than expected may be related to the duration of the treatment or the purity of the benfotiamine.

There was a trend for APOE  $\epsilon 4$  and sex related differences in thiamine response to benfotiamine but the differences were not significant (Figure 8). Thiamine levels after benfotiamine were about two times higher in females than males. Thiamine values were approximately 50% higher in APOE  $\epsilon 4$  carriers than non- APOE  $\epsilon 4$  carriers.

The concentrations of blood thiamine, ThDP, ThMP after benfotiamine treatment did not correlate with ADAS-cog scores ( $p=0.736$ ,  $0.917$ ,  $0.500$ , respectively) nor CDR ( $p=0.762$ ,  $0.896$ ,  $0.767$ , respectively).

#### **The response of advanced glycation end products (AGE) to benfotiamine treatment.**

Benfotiamine inhibited the increase in AGE over the course of the disease and the effect was more apparent in non- APOE  $\epsilon 4$  patients (Figure 9).

### **The response of FDGPET to benfotiamine treatment.**

The comparison of regions of interest is presented in Table 3D, using the paracentral lobule and cerebellum as the reference region. No significant differences were observed between the benfotiamine and placebo populations in the pre-specified regions of interest.

The multivariate pattern derived through the regression against CDR correlated negatively with CDR ( $p=0.002$ ) (Figure 10B) across all participants and time points. Robust positive loadings, i.e. with more than 97.5% of bootstrap loadings larger than zero, were found in the right precuneus, inferior parietal and mid frontal cortex: higher relative signal in these areas was associated with a better (=lower) CDR score. Robust negative loadings, i.e. with more than 97.5% of bootstrap loadings smaller than zero, were found in the bilateral paracentral lobules and bilateral cerebellum: higher relative signal at these locations was associated with a higher (=worse) CDR score. Pattern scores showed a significantly higher change from baseline to 12 months in treated than untreated participants (Figure 10A). However, a difference was observed between placebo and treatment arm at baseline ( $T=2.1582$ ,  $p=0.034$ ) when APOE status was not considered. Calculation of differences with sex was complicated by differences in the rates of the two groups at baseline.

Stratification by APOE  $\epsilon 4$  revealed that that the CDR-derived FDG PET pattern showed a treatment effect at 12 months in APOE  $\epsilon 4$  negative population ( $p=0.019$ ) but not in APOE  $\epsilon 4$  positive population ( $p=0.255$ ) (Figure 10C). In the APOE positive population there was no difference between treatment groups at baseline ( $p=0.164$ ); in the APOE negative population, pattern scores were higher at trend level ( $p=0.086$ ) in the benfotiamine group.

For 59 participants who completed follow-up, the longitudinal change in pattern score (follow-up minus baseline) also correlated negatively with the accompanying change in CDR score ( $R=-0.446$ ,  $p<0.001$ ). No difference in longitudinal change was observed between treated and untreated participants ( $p=0.638$ ). Additional analyses to adjust for any baseline differences and to explore other baseline heterogeneity effects or comparison patterns were deferred for subsequent evaluation.

## Discussion

The results show that benfotiamine administration in patients with aMCI and dementia due to AD is safe and successful in increasing peripheral thiamine levels. The trial provides preliminary evidence of efficacy of benfotiamine on cognitive and functional outcomes. In aggregate, our results provide proof of principle that justify testing the efficacy of benfotiamine in ameliorating cognitive and functional decline among participants with aMCI and dementia due to AD in a trial with a larger sample size and study duration. Measures of blood thiamine (a pharmacokinetic marker of drug delivery), FDGPET patterning (a CNS biomarker of synaptic activity) and serum AGE (a peripheral biomarker of metabolic dysregulation) provided further evidence of the effects of benfotiamine that could benefit cognition.

The results support benfotiamine's effectiveness which was reported in a preliminary study of five patients without placebo control that was published after our trial was initiated [36]. That study found that 300 mg daily of commercial benfotiamine over 18 months improved

MMSE by three points in with greater severity of dementia (i.e., MMSE of 12-25) than our patient population (MMSE>21). Levels of blood thiamine and thiamine esters were not reported in the previous study and too few patients were reported to examine sex or APOE effects.

The large increases in whole blood thiamine, ThDP and ThMP provided a robust indication that oral tablets effectively delivered the treatment. Indeed, the 161-fold increase serum thiamine was more robust than predicted, but the variation was large. The large increase in thiamine with relatively small increases in ThDP (twofold) and ThMP (fivefold) was also reported following benfotiamine in mouse brain [30]. Appreciable differences in thiamine levels were observed by sex (two-fold) and APOE-epsilon4 carrier status (three-fold) following treatment, but these observations need to be replicated in a larger sample.

The ability of blood thiamine or its esters to predict AD at baseline that was suggested by other trials [67-70] was not evident in our patients. Unlike previous studies which included more severe patients [68, 70], blood ThDP did not correlate significantly with MMSE (0.664), CDR (0.618) or ADAS-cog (0.883) at baseline or following benfotiamine. Thus, the baseline studies are not supportive of a critical role of blood ThDP in AD. Our studies do support the finding that ThDP is lower in females than males [67, 70]. These results suggest that thiamine, ThDP and ThMP should be tested in any subsequent study, and additional aspects of thiamine homeostasis such as cellular localization or ThDP effect on transketolase should be tested as well. At minimum, the blood measures provide a measure of drug delivery.

The significant correlation of MMSE and the normalized FDG PET at screening, as well as the correlation between CDR and the derived multivariate pattern, are consistent with the



well-documented tight relation of glucose metabolism to AD. Several factors may have contributed to the lack of FDG PET treatment effect findings despite the large measured changes in blood thiamine and observed differences in ADAS-cog changes. These include baseline heterogeneity in regional hypometabolism, the number of participants having both initial and post-treatment scans, use of CDR as the sole target outcome for the progression pattern, and the very small longitudinal changes that occur in FDG PET over 12 months in this mild population. Next steps include alternate apriori and data driven pattern-based analyses to further understand these relationships. As other potential considerations, the positive effects of benfotiamine/thiamine, including improved cognition, in neurodegeneration occur with minimal change in ThDP [33] [30, 31]. Thus, benfotiamine/thiamine could be acting at steps of glucose metabolism that do not change brain glucose uptake or by one of thiamine/benfotiamine's actions not directly linked to metabolism. Thiamine also regulates activities of enzyme like malate dehydrogenase and glutamate dehydrogenase [71]. Thiamine can act as an antioxidant [13] [19, 26, 72, 73] and may act directly in cholinergic transmission [74]. Thiamine serves as an allosteric regulator of many proteins [73]. Benfotiamine and thiamin may act as Nrf2 activators [30], which would help the brain deal with many oxidative insults. Finally, benfotiamine/thiamine could be acting on endothelial cells as has been demonstrated in studies of diabetes [20, 21, 37].

The CDR, FDGPET data, and AGE response to benfotiamine suggest that AD patients without APOE  $\epsilon 4$  were more responsive to benfotiamine in this study population. The diminished response did not seem to be a difference in drug availability since blood thiamine (+46%), and its esters were all higher in patients with APOE  $\epsilon 4$  following benfotiamine (not statistically significant). Patients with APOE  $\epsilon 4$  may have a more severe form of the disease

since they have more plaques and they occur earlier [75-77]. APOE  $\epsilon$ 4 carriers have higher levels of the glyoxal, fluorescent AGEs, N $\epsilon$ -carboxymethyllysine, and the receptor for AGE (sRAGE) ( $p=0.018$ ) when compared to non-carriers [78] .

The role of AGE in AD as a biomarker and progression of disease is not well developed. Recent studies demonstrate that the development of AGE parallels the development of the cognitive deficit [11]. The AGE pentosidine is an indicator of Alzheimer's disease [79]. Methylglyoxal and glyoxal levels in serum are higher in MCI patients. Methylglyoxal in serum distinguishes MCI from controls but not from AD. Meanwhile, serum glyoxal levels differentiate MCI from control and AD groups [35]. The levels of carboxymethyllysine in serum correlate negatively with the clinical cognitive as measured by MMSE [34]. AGE increase in healthy APOE  $\epsilon$ 4 and this may provide a link between APOE  $\epsilon$ 4 and AGE and our responses [78]. Both sex and APOE status alter the AD serum metabolome [80]. In animals, even mild thiamine deficiency leads to increases in AGE [81]. Increased AGE are common in diabetes, which predisposes to the development of AD, and there are many intriguing overlaps between diabetes and AD [18]. Benfotiamine prevents the micro and macro vascular damage in diabetes related to AGE [20, 37, 82]. The mechanisms for the protection have been studied extensively [83].

Our study has several limitations. Our sample size, while appropriate for a pilot study, was relatively small and of short duration, which particularly affected our subgroup analyses. Some significant findings in the secondary endpoints, subgroup analyses and multiple PET-related scores could be due to chance in the context of multiple comparisons without  $p$ -value correction. However, we believe that this approach is appropriate in the setting of a pilot study and inform the proposal of a larger confirmatory clinical trial. It is also important to point out

that the observed effects for primary and secondary outcomes were consistently in the direction of benefit for benfotiamine. Another potential limitation is our definition of AD. Our study participants had aMCI and dementia that met the criterion for the Alzheimer's continuum in the NIA/AA research framework [38], which we ascertained through amyloid positivity on PET scans. However, we cannot say with certainty that amyloid was the primary pathology causing cognitive impairment, as other pathologies that we did not ascertain could have caused the cognitive impairment. Lastly, the lack of ethnic and racial diversity is also of concern, and a larger trial must aim to recruit a sample with representation of all ethnic and racial groups.

In summary, benfotiamine is safe and cost effective, and the results of this pilot study are encouraging, providing preliminary evidence of efficacy. Our next step is to propose a larger clinical trial appropriately powered to replicate our findings. We believe that further studies would be very valuable to determine whether benfotiamine may be helpful in delaying onset or treating AD.

#### **Acknowledgements.**

We thank the patients and caregivers for their time and commitment. We also thank the following: Alzheimer Drug Discovery Foundation, NIA R01AG043679 (GEG), Burke Rehabilitation Hospital, Burke Neurological Institute, NIA R56AG062305 (SAF). NIH K24AG045334 (JAL) for funding, Advanced Orthomolecular Medicine for providing the benfotiamine (Dr. Traj Nibber), Dawn C. Matthews, M.S., M.B.A., ADM Diagnostics, Northbrook, IL, USA for help interpreting the imaging, Dr. Michael Reding, Dr. Mary Beth Walsh and Marina Harmon (Burke Rehabilitation Hospital) for their help. Sarah Mink and Tiffany Moy of the Burke Neurological Institut for their help with patient care.

Research reported in this publication was supported by the National Center For Advancing Translational Sciences of the National Institutes of Health under Award Number UL1TR000457. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health". Sonia Sequeir from this center was critical in preparing the IND. Lucien Bettendorff is Research Director of the Fund for Scientific Research (FNRS, Belgium,

Conflicts of Interests/Disclosure Statement. None of the authors has any conflicts to declare.

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## Table 1. Selection criteria for the patients

853 **Inclusion criteria.** Each patient met the following criteria:

- 854 • Subjects who are able and willing to provide informed consent.
- 855 • Male and non-pregnant, non-lactating, postmenopausal, or surgically sterilized female
- 856 subjects at least 60 years of age or older.
- 857 • Clinical diagnosis of amnesic MCI by the Peterson criteria or probable AD dementia
- 858 according to the National Institute of Neurological Disorders and stroke and the
- 859 Alzheimer's Disease related Disorders Association (NINCDS/ADRDA)
- 860 • MMSE score >21, CDR score >0.5 and <1 Cornell Scale for Depression in Dementia
- 861 (CSDD) score <10.
- 862 • Ambulatory or ambulatory with aide
- 863 • Has a caregiver willing to accompany the patient to each visit, accept responsibility for
- 864 supervising treatment and provided input to clinical outcome assessments
- 865 • Reside at home
- 866 • Speak English
- 867 • Amyloid positive PET-scan
- 868 • Patients taking FDA approved medications for the treatment of Alzheimer's Disease
- 869 [e.g., donepezil (Aricept), galantamine (Razadyne), rivastigmine (Exelon), or memantine
- 870 (Namenda)] for three months prior to baseline. Patients not on these medications did
- 871 not initiate them during the study.

872 **Exclusion criteria**

- 873 • Significant neurological disorder other than AD including hypoxia, stroke, traumatic brain
- 874 injury
- 875 • A current psychiatric disorder according the DSM-IV diagnosis of major depression
- 876 unless successfully treated on a stable dose of an antidepressant for at least 4 weeks
- 877 and continues on stable dose throughout the study
- 878 • Any other DSM-IV Axis I diagnosis including other primary neurodegenerative dementia,
- 879 schizophrenia or bipolar depression
- 880 • A current diagnosis of uncontrolled Type I or Type II diabetes mellitus [Hemoglobin A1 C
- 881 (Hb A1C <8]. Patients with uncontrolled diabetes (i.e., if glucose values exceed 200
- 882 mg/ml.
- 883 • A current diagnosis of active, uncontrolled seizure disorder.
- 884 • A current diagnosis of probable or possible vascular dementia according to NINDS-
- 885 AIREN.
- 886 • An investigational drug during the previous 4 weeks.
- 887 • Any previous exposure to Benfotiamine.
- 888 • A current diagnosis of severe unstable cardiovascular disease.
- 889 • A current diagnosis of acute severe, or unstable asthmatic condition (e.g., severe
- 890 chronic obstructive pulmonary disease (COPD),
- 891 • A current diagnosis of cardiac, renal or hepatic disease.
- 892 • A current diagnosis of cancer including any active treatment.
- 893 • History of alcoholism, current or within past 5 years.
- 894 • A disability that may prevent the patient from completing all study requirements (e.g.,
- 895 blindness, deafness, severe language difficulty).

**Table 2. Baseline comparison between benfotiamine (n = 34) and placebo (n = 36)**

**Table 2A. Baseline demographic characteristics.**

	Total	Placebo	Benfotiamine	P value
<b>Age</b>				<b>T</b>
Mean(SD)	75.77 (7.01)	75.81 (7.19)	75.74 (6.91)	0.967
<b>Gender</b>				<b>F</b>
Female	41 (58.6)	18 (50.0)	23 (67.6)	0.153
Male	29 (41.4)	18 (50.0)	11 (32.4)	
<b>Race</b>				<b>F</b>
Black	2 (2.9)	1 (2.8)	1 (2.9)	1.000
White	68 (97.1)	35 (97.2)	33 (97.1)	
<b>Ethnicity</b>				<b>F</b>
Hispanic/Latino	4 (5.7)	4 (11.1)	0 (0.0)	0.115
Not Hispanic/Latino	66 (94.3)	32 (88.9)	34 (100)	
<b>MMSE total</b>				<b>T</b>
Mean(SD)	25.33 (2.63)	25.33 (2.52)	25.32 (2.78)	0.988
<b>Dichotomized MMSE</b>				<b>F</b>
< 26	34 (48.6)	18 (50.0)	16 (47.1)	0.816
>= 26	36 (51.4)	18 (50.0)	18 (52.9)	
<b>APOE genotype</b>				<b>F</b>
'2, 3'	4 (5.7)	2 (5.6)	2 (5.9)	0.883
'2, 4'	1 (1.4)	0 (0.0)	1 (2.9)	
'3, 3'	24 (34.3)	14 (38.9)	10 (29.4)	
'3, 4'	34 (48.6)	17 (47.2)	17 (50.0)	
'4, 4'	7 (10.0)	3 (8.3)	4 (11.8)	

T: t-test (with equal variances); "Fisher's exact t" test

**Table 2B. Baseline neuropsychological outcome measures**

	<b>Total</b>	<b>Placebo</b>	<b>Benfotiamine</b>	<b>P value</b>
<b>ADAS total score</b> (ITT)	15.34 (6.36)	15.50 (6.61)	15.19 (6.16)	0.835 t
<b>ADAS total score</b> (Per protocol)	15.34 (6.40)	15.48 (6.70)	15.19 (6.16)	0.849 t
<b>CDR score</b> Median(range)	0.50 (0.50 - 1.00)	0.50 (0.50 - 1.00)	0.50 (0.50 - 1.00)	0.334 w
<b>ADCS-ADL total score</b>	47.44 (4.29)	47.42 (4.65)	47.47 (3.95)	0.959 t
<b>NPI</b>	13.50 (10.44)	11.03 (10.15)	16.12 (10.23)	0.040 t
<b>Buschke score</b>	27.09 (9.74)	26.03 (9.01)	28.21 (10.49)	0.354t

Values are Mean (SD). T denotes t-test (with equal variances). W Wilcoxon rank sum test

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**Table 2C. Baseline Thiamine, ThDP and ThMP .**

	<b>Total</b>	<b>Placebo</b>	<b>Benfotiamine</b>	<b>P Value</b>
<b>Thiamine</b>				
Mean(SD)	<b>5.72 (11.31)</b>	<b>5.26 (4.50)</b>	6.20 (15.56)	0.735
<b>Thiamine diphosphate</b>				
Mean(SD)	69.71 (19.40)	74.46 (20.21)	64.82 (17.50)	0.038
<b>Thiamine monophosphate</b>				
Mean(SD)	3.21 (1.72)	3.46 (1.83)	2.97 (1.59)	0.250

901 Comparisons were by t-test (with equal variances);

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**Table 2D. Baseline comparison of FDGPET**

	<b>Total</b>	<b>Placebo</b>	<b>Benfotiamine</b>	<b>P value</b>
<b>Posterior cingulate</b>				
Left	0.85 (0.09)	0.83 (0.10)	0.87 (0.08)	0.087
Right	0.81 (0.07)	0.79 (0.07)	0.82 (0.06)	0.069
<b>Percuneus</b>				
Left	1.09 (0.09)	1.08 (0.10)	1.10 (0.08)	0.332
Right	1.09 (0.10)	1.08 (0.11)	1.11 (0.09)	0.287
<b>Medial temporal</b>				
Left	0.97 (0.11)	0.94 (0.11)	1.00 (0.10)	0.022
Right	1.01 (0.12)	0.98 (0.12)	1.04 (0.10)	0.020
<b>Frontal cortex</b>				
Left	0.99 (0.09)	0.98 (0.09)	0.99 (0.09)	0.480
Right	1.01 (0.09)	1.00 (0.09)	1.03 (0.08)	0.268
<b>Hippocampus</b>				
Left	0.74 (0.08)	0.74 (0.08)	0.75 (0.08)	0.938
Right	0.76 (0.09)	0.75 (0.10)	0.76 (0.08)	0.764
<b>Entorhinal_cortex</b>				
Left	0.88 (0.13)	0.88 (0.14)	0.87 (0.13)	0.693
Right	0.89 (0.18)	0.87 (0.21)	0.90 (0.14)	0.477
<b>Prefrontal_cortex</b>				
Left	0.82 (0.09)	0.81 (0.09)	0.83 (0.08)	0.417
Right	0.87 (0.09)	0.86 (0.10)	0.88 (0.08)	0.293
<b>Whole brain</b>	0.88 (0.05)	0.87 (0.06)	0.89 (0.05)	0.122

All values were normalized to the cerebellum as described in methods. All values are mean (SD). All comparison were by the t-test (equal variances).

**Table 3. Consequences a 12 month treatment with benfotiamine.**

Table 3A. Benfotiamine did not cause any adverse events.

<b>SYMPTOM</b>	<b>PLACEBO (n = 36)</b>	<b>TREATMENT (n = 34)</b>
Anxiety	4 (11%)	5 (14%)
Bruise	5 (14%)	2 (6%)
Cold symptoms	3 (8%)	3 (8%)
Depression	2 (6%)	1 (3%)
Dizziness	3 (8%)	3 (8%)
Fall	12 (34%)	6 (17%)
Head injury	2 (6%)	0 (0%)
Heart arrhythmia	2 (6%)	1 (3%)
Pain	4 (11%)	5 (14%)
Pneumonia	3 (8%)	0 (0%)
Sprain	2 (6%)	0 (0%)
Surgery	3 (8%)	1 (3%)
Allergy	2 (2%)	0 (0%)
Gastrointestinal problem	12 (34%)	9 (26%)
Stroke	0 (0%)	2 (6%)
<b>Total</b>	<b>59</b>	<b>38</b>

**Table 3B. Changes in ADAS-cog following twelve month treatment with placebo or benfotiamine (ITT and per-protocol analysis)**

**[Unadjusted comparison of the changes form baseline to month\_12 in ADAS score between intervention and control (ITT data after LOCF imputation)]**

Variable	Total	Placebo	Benfotiamine	<i>P</i> <sup>1</sup>
<b>ADAS score change</b>				
Mean(SD)	2.37 (5.61)	3.26 (5.52)	1.39 (5.63)	0.162 <sup>[T]</sup>

Repeated measures ANOVA *P*-value: 0.5626  
Mixed effect model *P* value: 0.0708  
GEE *P* value: 0.1373  
Wilcoxon Rank sum *P*-value: 0.0980  
1 *P* values obtained from the statistical tests: [T] t-test (equal variances)

**Table 3B. Unadjusted comparison of the baseline to month\_12 in ADAS score between benfotiamine and control (Per-protocol)**

Variable	Total	Placebo	Benfotiamine	<i>P</i> <sup>1</sup>
<b>ADAS score change</b>				
Mean(SD)	2.10 (5.59)	3.2 (5.66)	0.96 (5.41)	0.125 <sup>[T]</sup>

Repeated measures ANOVA *P*-value: 0.355  
Mixed effect model *P*-value: 0.056  
GEE *P*-value: 0.107  
Wilcoxon Rank sum *P*-value :0.069  
1 *P* values obtained from the statistical tests: [T] - T-test (equal variances);



**Table 3C. Changes in Thiamine, ThDP and ThMP after 12 months of placebo (n=36) or benfotiamine (n=34).**

**Changes in thiamine and its esters after 12 months of placebo**

	Baseline	12 months	P value
Thiamine	5.48±0.77	13.64±4.06	0.044
Thiamine diphosphate	74.46±3.42	91.70±7.94	0.044
Thiamine monophosphate	3.38±0.31	4.05±0.73	0.382

**Changes in thiamine and its esters after 12 months of benfotiamine**

	Baseline	12 Months	P value
Thiamine	6.20±2.67	999.51 ± 147.4	< 0.001
Thiamine diphosphate	64.82±3.00	197.39 ± 17.75	< 0.001
Thiamine monophosphate	2.97±0.27	20.73 ± 2.16	< 0.001

Comparisons were by t-test (with equal variances);

**Table 3D. Comparison of the Month\_12 - Baseline change in FDGPET between benfotiamine (n = 34) and placebo (n = 36)**

	<b>Total</b>	<b>Placebo</b>	<b>Benfotiamine</b>	<b>P value</b>
<b>Posterior cingulate</b>				
Left	-0.03 (0.03)	-0.03 (0.04)	-0.02 (0.03)	0.629
Right	-0.02 (0.03)	-0.02 (0.03)	-0.02 (0.03)	0.742
<b>Parietal</b>				
Left	-0.02 (0.04)	-0.03 (0.04)	-0.02 (0.05)	0.448
Right	-0.03 (0.04)	-0.03 (0.04)	-0.02 (0.04)	0.323
<b>Percuneus</b>				
Left	-0.03 (0.04)	-0.02 (0.04)	-0.03 (0.04)	0.719
Right	-0.03 (0.04)	-0.03 (0.04)	-0.03 (0.04)	0.722
<b>Medial temporal</b>				
Left	-0.03 (0.04)	-0.03 (0.04)	-0.03 (0.04)	0.956
Right	-0.03 (0.05)	-0.03 (0.05)	-0.03 (0.05)	0.748
<b>Frontal cortex</b>				
Left	-0.02 (0.04)	-0.02 (0.04)	-0.03 (0.04)	0.646
Right	-0.02 (0.04)	-0.02 (0.04)	-0.03 (0.04)	0.616
<b>Hippocampus</b>				
Left	-0.02 (0.04)	-0.02 (0.05)	-0.01 (0.04)	0.451
Right	-0.02 (0.04)	-0.02 (0.05)	-0.02 (0.04)	0.503
<b>Entorhinal_cortex</b>				
Left	-0.02 (0.11)	-0.01 (0.10)	-0.02 (0.11)	0.774
Right	-0.02 (0.09)	-0.01 (0.08)	-0.02 (0.10)	0.502
<b>Prefrontal_cortex</b>				
Left	-0.02 (0.04)	-0.02 (0.04)	-0.02 (0.04)	0.742
Right	-0.02 (0.04)	-0.02 (0.04)	-0.03 (0.04)	0.559
<b>Whole_brain</b>	-0.01 (0.02)	-0.02 (0.02)	-0.01 (0.02)	0.753

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Figure 1.

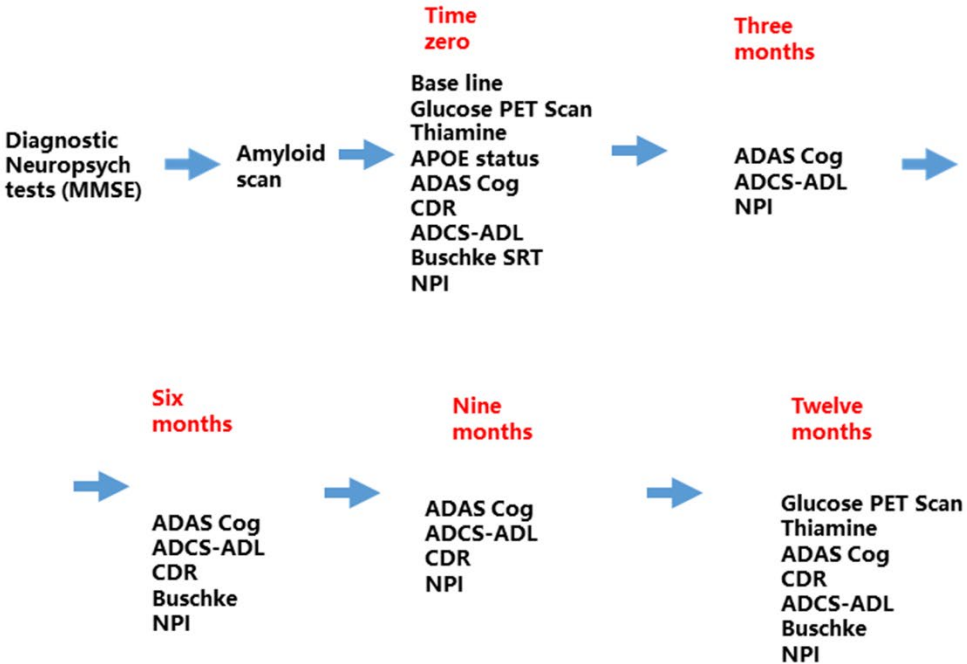


Figure 2.

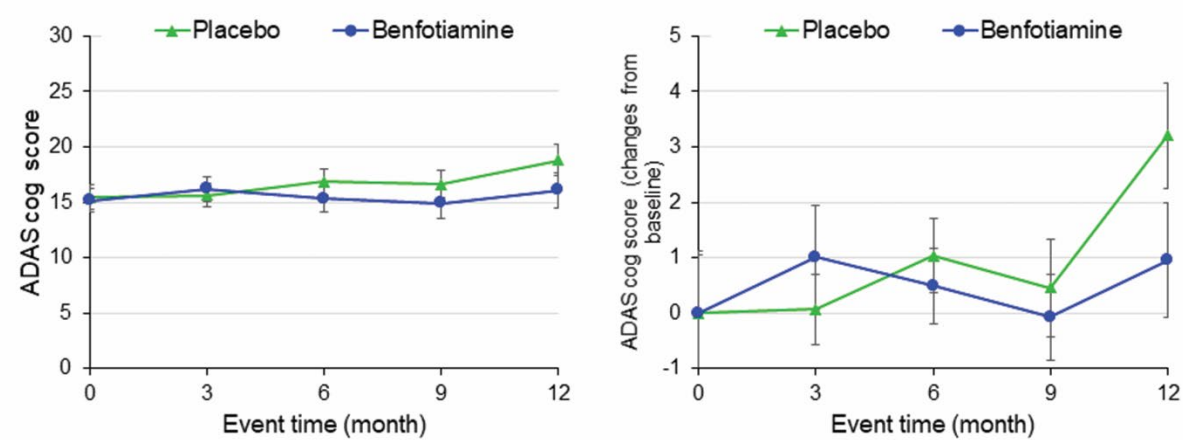
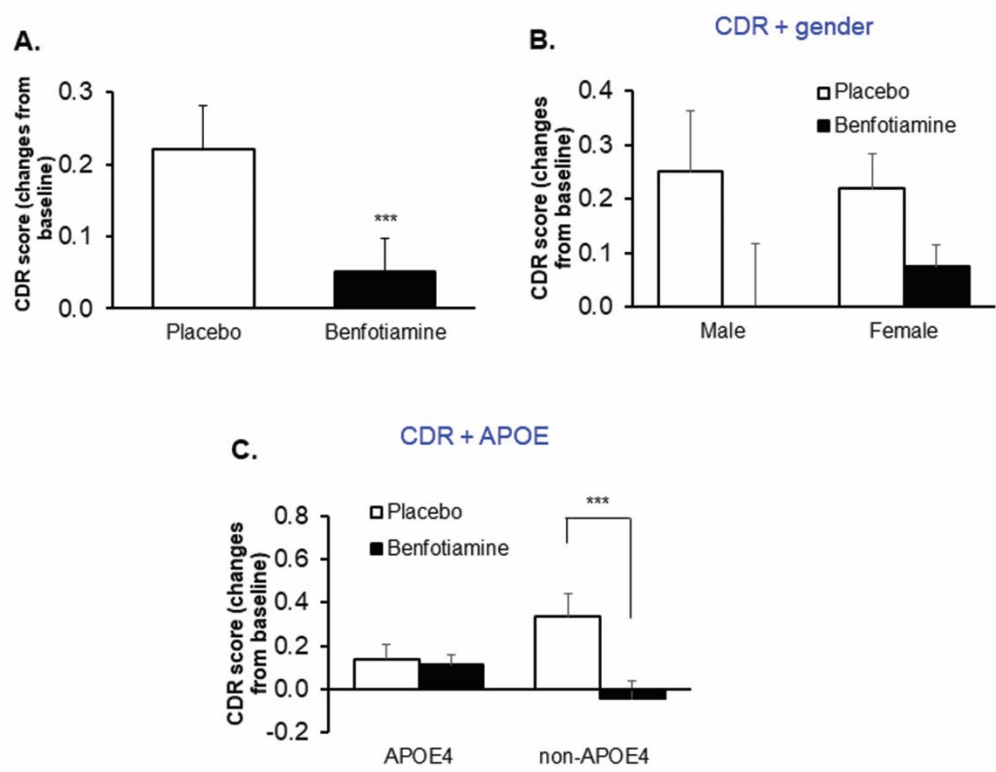


Figure 3.



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Figure 4.

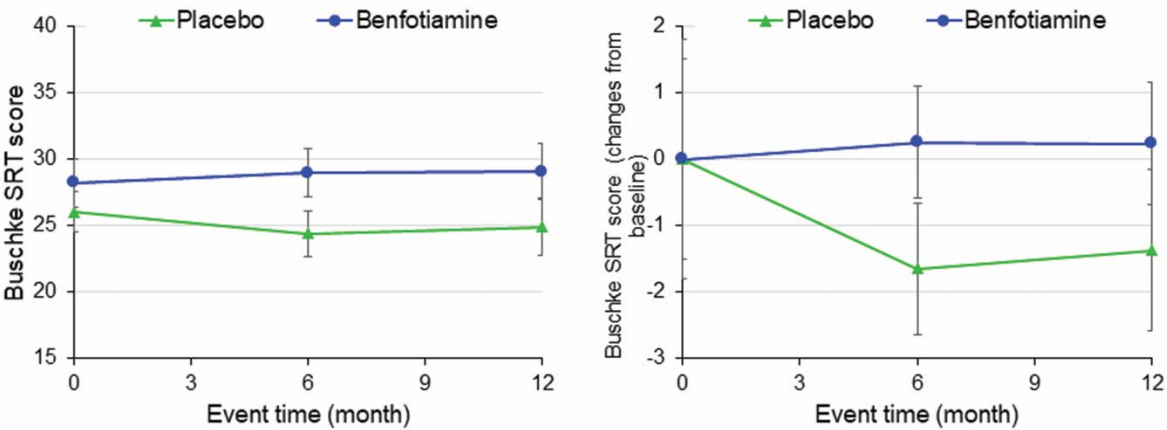


Figure 5.

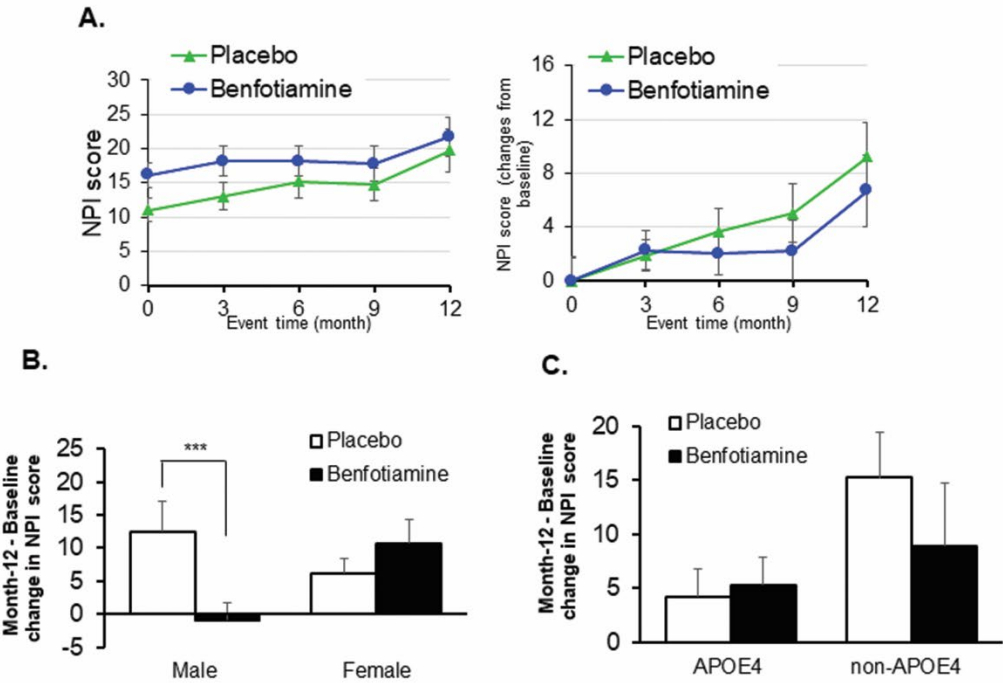


Figure 6.

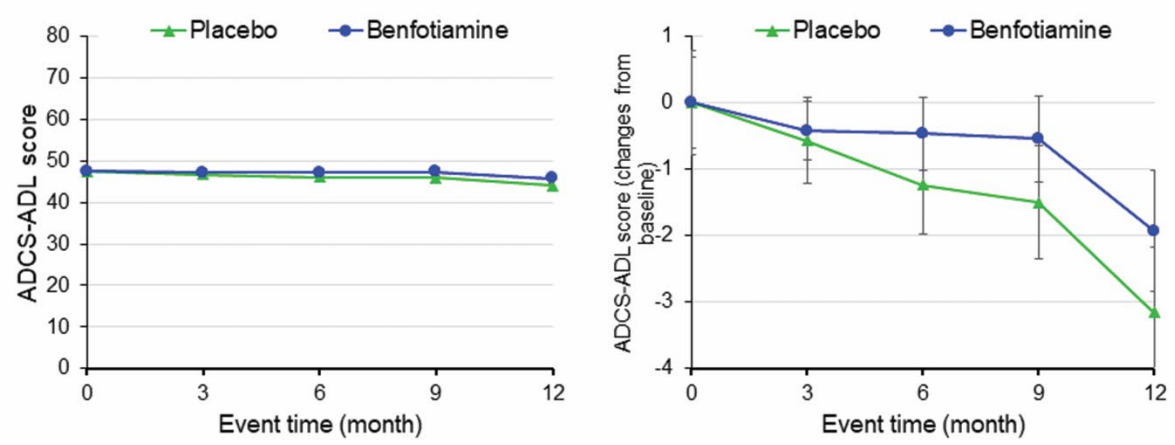
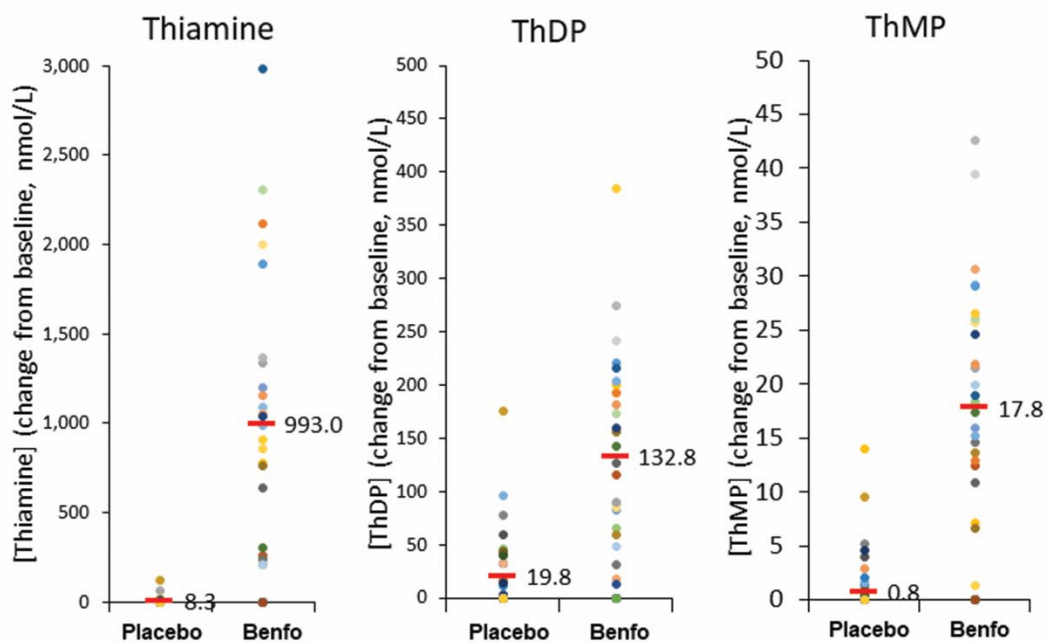




Figure 7.



**Figure 8.**

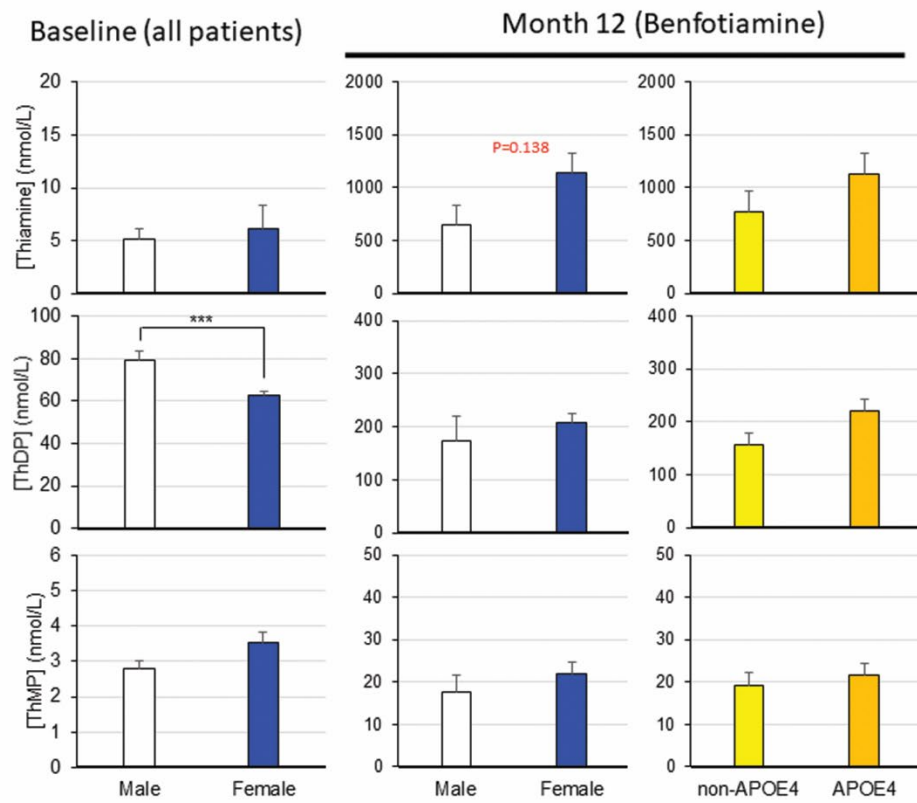


Figure 9.

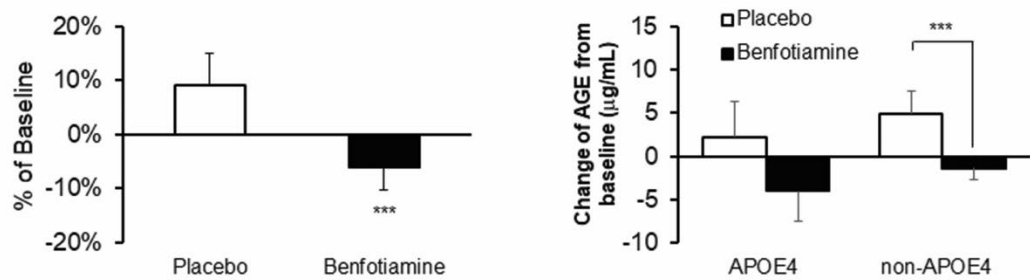


Figure 10A.

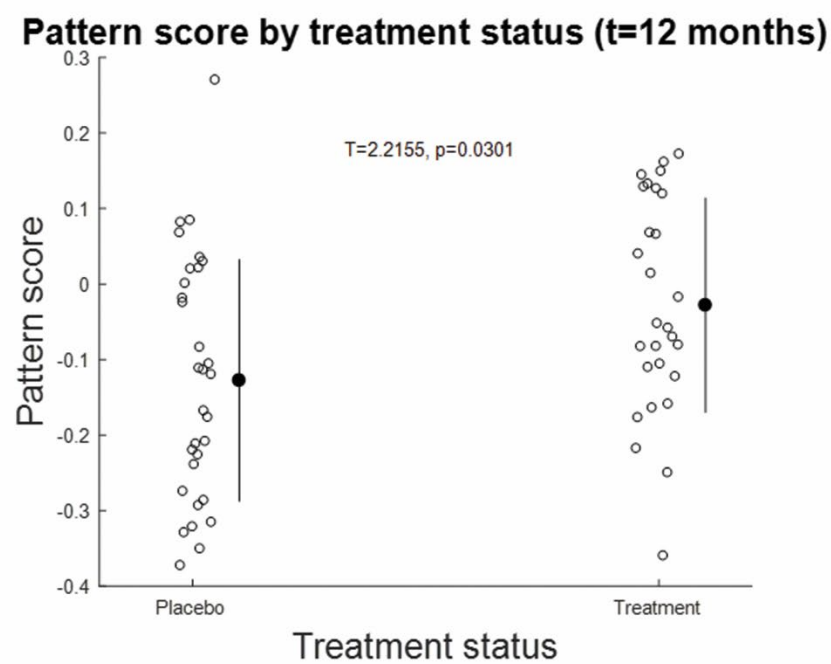


Figure 10B.

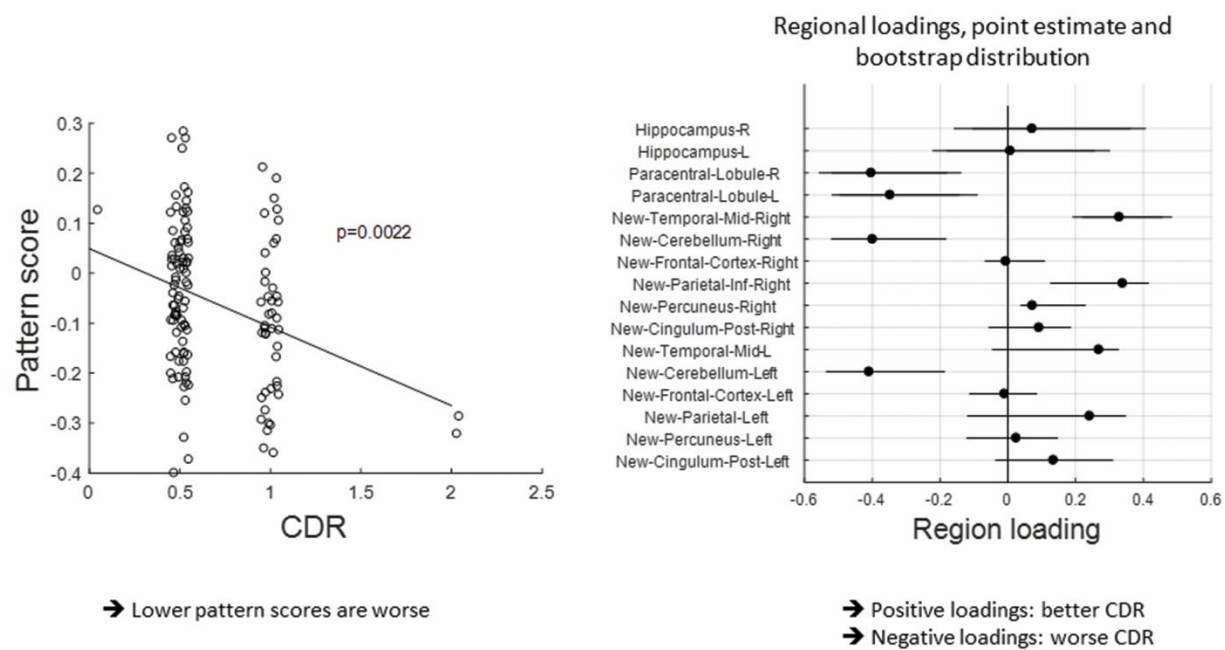
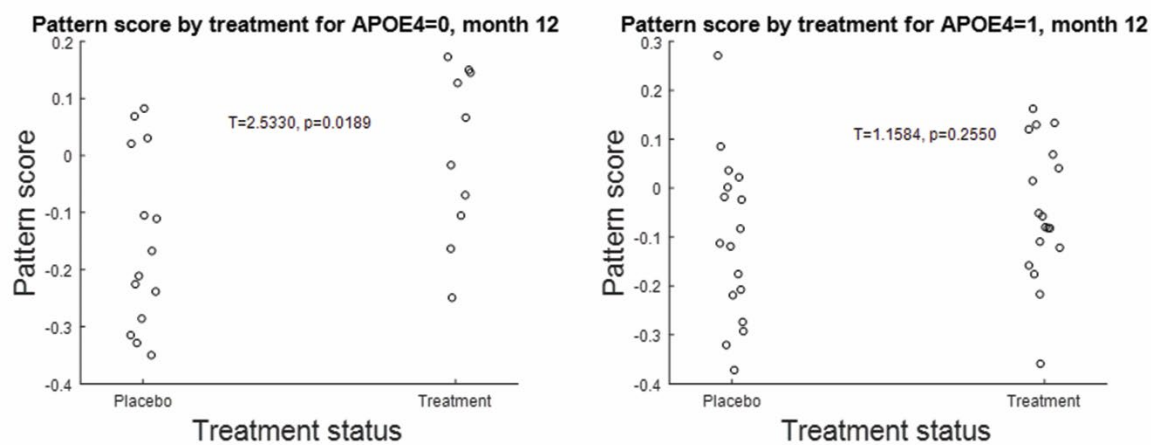


Figure 10C.



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## Figure Legends

**Figure 1.** Summary of the treatment protocol for the one year trial.

**Figure 2.** Changes in ADAS cog with benfotiamine treatment compared to controls.

See Table 7 for statistical comparisons.

**Figure 3.** Benfotiamine treatment and the CDR. CDR Placebo = 34, benfotiamine = 29. On the figure \*\*\* indicates significantly different ( $p=0.034$ ) (A). When the groups are also separated by sex, large but non-significant differences occur (B). When the groups are separated by APOE4 only the non-APOE  $\epsilon 4$  allele group differs. In the non-APOE4 group the \*\*\* indicates values significantly different ( $p=0.013$ ) (C). The APOE4 denotes at least one  $\epsilon 4$  allele. P values here are when there are subgroups are all obtained from subgroup analysis, not interaction from ANOVA (C).

**Figure 4.** Benfotiamine and the Buschke Selective Reminding Test (SRT)

**Figure 5.** Benfotiamine and the Neuropsychiatric Inventory (NPI). No differences were seen in the overall scores (Figure 5A). However, separation of the groups by sex revealed a highly significant benefit in males but not females. \*\*\* indicates  $p=0.035$  (Figure 5B). No significant difference was seen with APO  $\epsilon 4$  alleles (Figure 5C).

**Figure 6.** Alzheimer's Disease Cooperative Study-Activities of Daily Living (ADCS-ADL)

**Figure 7.** Blood thiamine, ThMP, and ThDP concentrations at baseline and month 12. Each dot represents a different patient. The bar represents the mean value. All values are per protocol

after omitting a patient designated as placebo who was taking benfotiamine from another source.

**Figure 8.** Relation of sex and APOE  $\epsilon 4$  genotype to thiamine, ThDP and ThMP. Values are means  $\pm$  SEM. \*\*\* Denotes significantly different ( $p < 0.0001$ ) by t-test.

**Figure 9.** Advanced Glycation End Products (AGE) after benfotiamine treatment. These were done as an exploratory analysis. They were measured on serum and several samples were contaminated with RBC. In the left panel, the n's are 12 placebo and 13 benfotiamine patients. The asterisk indicates  $p = 0.043$ . In the right panel, in the APO  $\epsilon 4$  group the  $n = 6$ . In the non-APOE4 group  $n = 7$ . The APO  $\epsilon 4$  denotes at least one  $\epsilon 4$  allele.

**Figure 10A.** Pattern score as function of the 12 month treatment period. The pattern is a linear combination of the first 2 Principal Components whose pattern score is slightly but significantly higher for treatment than untreated participants at time point 12 months.

**Figure 10B.** The left panel shows the pattern score plotted against CDR status (p-level obtained from whole-model F-test.) A higher pattern score implies lower CDR status. The right panel shows loading distributions from a bootstrap test with 90% coverage intervals. We stress that these loadings sizes and signs are relative since we removed the whole-brain mean from the analysis prior to the pattern derivation. Thus, high positive loadings are found in the right Mid temporal and inferior parietal cortex, implying relatively higher signal in participants with lower CDR. Bilateral cerebellum and paracentral lobule on the other hand, had relatively lower signal in participants with lower CDR.

**Figure 10C.** Stratification of the pattern score by APOE status reveals that APOE4 negative patients show the greatest response. APOE  $\epsilon 4 = 0$  patients show a treatment effect (left panel),



981 APOE  $\epsilon$ 4=1 do not (right panel).

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